Swansea University - CSC309 Invention and Innovation in Computing

NASA: The Apollo Guidance Computer

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Abstract

This paper discusses the history of the Apollo Guidance Computer. We discuss the people who contributed and helped develop the computer. We discuss where and how it was created and the role it played in getting the first man to step on the moon. Without this device and the contributing people, the Apollo 11 mission would not have been successful and through this paper you will understand why.

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Chapter 1

Motivations

1.1 Wide-Scale Motivations

I believe that most people you talk to will know about Neil Armstrong being the first man to step on the moon during the Apollo 11 mission, however the majority will not know about the technology and people behind the scenes that were crucial for the success of this milestone for mankind. The Apollo Guidance Computer contributed to the first moon landing and is an important part of the technological history for space exploration and navigation. Without the computers on board of the Apollo spacecraft, there would have been no moon landing. “A pilot was not capable of navigating to the moon, the calculations required to make in-flight adjustments and the complexity of the thrust controls outstripped human capacities” [1].

The Space Race was a competition between the United States and the Soviet Union. They wanted to achieve superior spaceflight capabilities. The United States were highly motivated to get to the moon before the Soviet Union as they had sent the first human to space with Yuri Gagarin’s orbital flight on 12th April 1961. John F. Kennedy set the goal of landing a man on the moon before the end of the decade, this goal really set the mission in motion and raised the stakes on the competition.

Spaceflight as a whole is extremely important, it helps us address questions about the Universe and our solar system. By attempting spaceflight, technology advances, new industries are created, and peaceful connections are made with other countries and nations. As NASA state on their website: “Curiosity and exploration are vital to the human spirit and accepting the challenge of going deeper into space will invite the citizens of the world today and the generations of tomorrow to join NASA on this exciting journey” [2].

1.2 Personal Motivations

I have always been interested in the universe and space travel, from wanting to be an astronaut at an early age to seeing a rocket launch during my holiday to Florida in 2015. I am subscribed to the New Scientist magazine, where new advances with space travel are often discussed. This course gave me an opportunity to write about something I am passionate about and enjoy. I think that choosing to write about a topic I enjoy is very important for this paper as I am very motivated to give a thorough and well thought out report.

Chapter 2

Background Information and Navigation

2.1 History of NACA

The National Advisory Committee for Aeronautics (NACA) was a United States federal agency founded on the 3rd of March 1915. Its purpose was to "undertake, promote and institutionalise aeronautical research" [3]. It was established by the federal government, serving as an emergency measure during World War 1. On the 29th of January 1920 President Wilson appointed Orville Wright, a pioneering flier and aviation engineer, to NACA's board. Their mission was to promote military and civilian aviation through research and they to look beyond the current needs. NACA was responsible for the "thin air foil theory" in the 1920s, the "NACA engine cowl" in the 1930s, the "NACA air foil" series in the 1940s and the "area rule" for supersonic aircrafts in the (1950s).

NACA technology also influenced World War II technology. Major engine manufacturers were having problem producing superchargers that would let the Boeing B-17 maintain power at a high altitude. With the help of engineers from NACA, they found solutions for these problems and created testing methods to help produce effective superchargers. The majority of aircrafts used forced induction, and this relied on information that had been developed by NACA.

From 1946 NACA had been experimenting with rocket planes, an example of this was the supersonic Bell X-1 [4]. The early 1950s brought along a challenge to launch a satellite for the International Geophysical Year. On the 4th of October 1957 the Soviets space program were successful in launching the world's first artificial satellite which they named Sputnik 1. As a result of this the United States were alarmed by the threat their national security and technological leadership, this led President Dwight D. Eisenhower to take action. This resulted in having scientists that were committed to research and for the Pentagon to match the Soviet military achievement. There was also a strong public interest in space exploration.

2.2 Creation of NASA

On the 12th of January 1958, NACA organised a "Special Committee on Space Technology" which was led by Guyford Stever – an American engineer [5]. The plan was to create a new federal agency that would conduct all non-military space activity. On the 29th of July 1958, President Eisenhower signed the National Aeronautics and Space Act which established NASA. They were responsible for the civilian space program as well as aeronautics and space research. NASA was created to have a more civilian orientation and to encourage peaceful applications in space science. They began operations on the 1st of October 1958 and absorbed the NACAs 8,000 employers and annual budget of $100 million. They also absorbed three major research laboratories: Langley Aeronautical, Ames Aeronautical and Lewis Flight Propulsion Laboratory.

2.3 General Information

Since being formed most of the US space exploration efforts have been led by NASA, these include the Apollo missions, the Skylab space station and more recently the space shuttle. The Apollo program was the third US human spaceflight program led by NASA and ran from 1961 to 1972. It was conceived during President Dwight Eisenhower administrations as a 3-person spacecraft to follow in the steps of project mercury, which was a one-person spacecraft, which put the first Americans in space. The program was dedicated to President John F Kennedy's national goal of "landing a man on the moon and returning him safely to earth". America was in a space race with the Soviet Union to accomplish this milestone. Being more fuelled after the Soviets put the first man in space.

2.4 Navigation

Navigation is a field of study that "focuses on the process of monitoring and controlling the movement of a craft or vehicle from one place to another" [52]. The 4 general categories for navigation are land, marine, aeronautics and space.

Longitude and latitude are used to find the position of any place on the Earth's surface. Latitude lines run in the direction of east to west across the Earth and longitude lines run from north to south.

For the Apollo program the guidance system had accelerometers that sensed changes in the craft's velocity or direction. The computer received flight plan data from the grounds tracking stations. The astronauts also fed information inro the computer during the flight [53].

Guidance computers are used to control the movement of vehicles, in my case a rocket. Guidance is the "process of calculating the changes in position, velocity, altitude, and/or rotation rates of a moving object required to follow a certain trajectory and/or altitude profile based on information about the object's state of motion" [54]. We are taught that in space there is no up but during space travel up can be whatever direction you want.

Chapter 3

What is the Apollo Guidance Computer (AGC)?

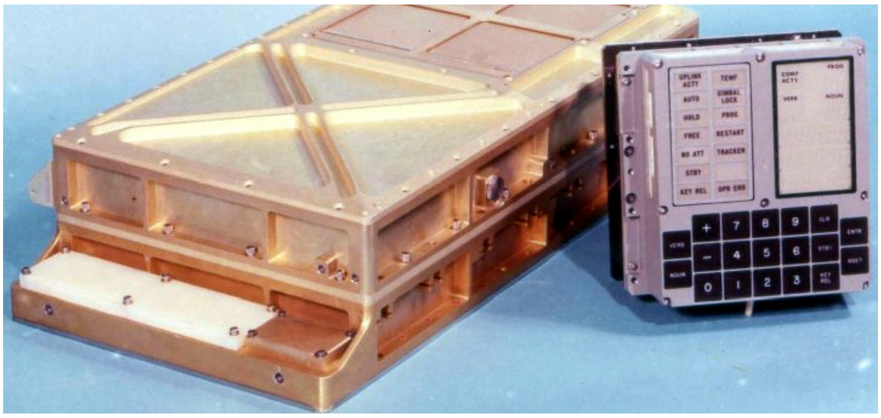

Figure 1: Apollo Guidance Computer

3.1 Apollo Guidance Computer

During the early years of spaceflight astronauts flew using control sticks, during the Apollo program computers flew most of the mission. The apollo guidance computer was a digital computer produced for the Apollo program in 1966. It was the first silicon integrated circuit-based computer [6]. The AGC provided computation and electronic interfaces for guidance, navigation and control of the spacecraft. It was manufactured by Raytheon and invented by the Charles Stark Draper Laboratory. The device weighed 32 kg and was 61x32x17cm. This is just a brief section to give you an idea of what the AGC is, I will be going into greater detail of the device and people behind it in the following chapters.

3.2 Apollo Command Module


Figure 2: Apollo Command Module

The AGC was installed on the Apollo Command Module which can be seen in figure 1. The command module was a truncated cone measuring at 10 feet and 7 inches with a diameter of 12 feet and 10 inches across the base. The command module housed the crew, spacecraft operations systems, re-entry equipment and the Service Module [7]. The cone used thrusters to provide altitude control.

3.3 Apollo Lunar Module


Figure 3: Apollo Lunar Module

The AGC was also installed on the Apollo Lunar Module which was the lander spacecraft that flew between orbit and the moon’s surface during the mission during the Apollo Program. The lunar module was attached to the command module for parts of the spaceflight. With the legs extended the module was 22 feet and 11 inches tall with a diameter of 31 feet [8].

Chapter 4

Important People & MIT Instrumentation Laboratory

4.1 Charles Stark Draper


Figure 4: Charles Stark Draper

Charles Stark Draper known by his peers as “Doc” was an American scientist and engineer. He was known as the “father of inertial navigation” [9]. He was born on the 2nd of October 1901 in Windsor, Missouri. In 1917 he attended the University of Missouri before transferring to Stanford University, California in 1919. He graduated in 1922 with a B.A. in psychology. He continued his studies at MIT earning a Bachelor of Science degree in electrochemical engineering (1926), a Master of Science in 1928 and Doctor of Science (1938) degrees in physics [10]. Charles’s cousin – Lloyd C. Stark, was also a prominent figure serving as 39th Governor of Missouri.

After finishing his PHD Draper began teaching at MIT, he was the assistant professor and taught aircraft instrumentation. In 1939 he became the lead professor in aeronautical engineering and founded the Instrumentation Laboratory. Charles interest in flight instrumentation was influenced by becoming a pilot in the 1930s, he was not able to become an Air Corps pilot but learned to fly by enrolling in a civilian course [11]. Draper also operated a consulting business to further his academic and industrial connections. Draper was known to be very charismatic; he drove around the MIT campus in a sports car and was interactive with the press about different sporting stories. He was named by Times magazine as one of the "Men of the Year" in January 1961.

Draper was a pioneer for inertial navigation, the technology used in spaceships, aircrafts and submarines. It enabled vehicles to navigate by sensing changes in direction and speed. He was most well-known for contributing towards to Apollo program, helping with the development of the Apollo Guidance Computer. After President John F. Kennedy's national goal of reaching the moon was set Charles and his laboratory were handed the first contract given out for the Apollo program [12].

Charles taught and was involved with research at MIT until January 1970, it was said that most of his energy was devoted during his final decade completing the Apollo computers and software [13]. In 1981 Charles was inducted into the National Inventors Hall of Fame for his scientific contributions and was a member of the inaugural class to the International Space Hall of Fame. He received a number of awards including the Howard N. Potts Medal in 1970 and the National Medal of Science from President Lyndon B. Johnson in 1964. He unfortunately died 85 years old in the Mount Auburn Hospital in Cambridge, Massachusetts. The Chairman of the MIT Corporation credited him for creating a "whole new industry in inertial instruments and systems for airplanes, ships, submarines, missiles, satellites and space vehicles" [14]. After his death the National Academy of Engineering established the Charles Stark Draper Prize in 1988 on behalf of his laboratory at MIT. The prize is awarded annually and is a $500,000 cash reward. It aims to "increase public understanding of the contributions of engineering and technology to the welfare of humanity" [15]. He was a fantastic man who left behind a massive legacy.

4.2 Eldon C. Hall

Figure 5: Eldon C. Hall with an Apollo Guidance Computer

Eldon Hall is an American physicist who was the leader of the hardware design for the Apollo Guidance Computer. He grew up in Oregon and completed his AB in Mathematics at Eastern Nazarene College in Massachusetts [16]. He went on to complete an AM in physics at Boston University and a PHD in physics from Harvard. In 1952 he was hired by the MIT Instrumentation Laboratory and first worked on random processes in control systems and then became interested in digital computing [17]. After coming from a physics background, he had to learn much of the digital computer engineering from scratch. Eldon was responsible for encouraging the Navy to use digital guidance computers in the Polaris missile project after working with MIT engineers to develop analogue-to-digital conversions for guidance systems. While working for Polaris developing digital guidance systems, he was promoted to group leader and formed the Digital Development Group at MIT [18]. The first successful flight of Polaris took place in 1960 this led his group being placed to work on the Apollo Guidance Computer after MIT were awarded the contract in 1961 [19]. During the Apollo program Eldon was the leader of the hardware design for the Apollo Guidance Computer. He was known for pioneering the use of integrated circuits in his design. He had been interested in these circuits from very early in their development, he spent time with both Jack Kirby at Texas Instruments and Robert Noyce at Fairchild Semiconductor in the late 1950s and early 1960s [20]. He convinced NASA in 1962 that integrated circuits were the correct technology for the computer and continued to lead the design effort until 1969. Eldon continued to work at the instrumentation laboratory until his retirement in 1988. During his retirement he authored the book "Journey to the Moon" which was his history of the Apollo Guidance Computer.

4.3 MIT Instrumentation Laboratory

Figure 6: Dr Draper in front of the laboratory

Beginnings

In 1932 Dr Draper founded a teaching laboratory with the goal of developing instrumentation needed for aircraft navigation. The lab gave students a chance to have hands on experience with new technology, however over the next few years it became a full-time laboratory. During the second World War the laboratory was expanded and moved into an old shoe polish factory In Cambridge's Massachusetts Avenue and became known as the Confidential Instrument Development Laboratory (CID). They produced early guidance systems and gyroscopic equipment which led to the Mark 14 Gunsight being created, it was widely spread with 85,000 units being ordered by the U.S Navy [21]. The gunsights were produced at a company called Sperry Gyroscopes and by helping with development Draper's reputation grew within the military and MIT as the gunsight's royalties became a source of funding for the university [22]. After the war the laboratory continued to design fire control systems. In 1949 they demonstrated a system that incorporated celestial references for improved accuracy. The lab continued to develop inertial navigation and in 1953 the lab's 2,700-pound Space Inertial Reference Equipment (SPIRE) system guided a B-29 bomber from Massachusetts to Los Angeles without a pilot [23]. Charles Draper and several associates flew aboard with the journey lasting 12 hours. In 1954, the laboratory introduced the first self-contained submarine navigation system (SINS) [24].

Cold War

A new era of ballistic missiles was made possible with the lab precision gyroscopes and accelerometers which could not be jammed like the existing radio guidance systems. After the successful launch of the Sputnik satellite by the Soviet Union in 1957, a new urgency was brought to the U.S Air Force Thor intermediate range ballistic missile (IRBM) program [25]. The same year the work started on the Polaris guidance system and before the end of the decade the laboratory started work on the FLIMBAL – floating inertial measurement ball, inertial guidance system and also the Mars Probe project. The laboratory gained validation for its inertial guidance system after the success of the Titan and Poseidon missile programs in the 1960s. The lab is most well-known for its part in the Apollo 11 moon landing. They received NASA's first contract for the Apollo program on the 10th of August 1961 and used the design work from their unlaunched Mars Probe as well as the Polaris missile program to help construct the guidance computer [26]. The lab also played a part in the following missions, during Apollo 13 they recommended the fix after the famous, "Houston we have a problem" and during Apollo 14 they transmitted a program to the crew who had been dealing with a malfunctioning switch. By the late 1960s the lab employed 2,000 people [27].

Vietnam Conflict

In 1971 NASA gave the laboratory a contract for the avionics of the Space Shuttle and in 1972 the first digital fly-by-wire system has been developed, which is a computer regulated flight control system that replaces mechanical flight controls with an electronic interface [28]. In 1973 they produced the algorithms for the Skylab's guidance and control system.

The laboratory was faced with protestors who were against the Vietnam War and the labs' role in developing military weapons. The lab was controversially renamed after Charles Draper and as a result led him into a brief retirement in 1970, this however was short lived, and he returned. In 1973 the laboratory split from MIT and become a not-for-profit organisation. The labs first president and CEO was appointed, Robert Duffy – a retired Air Force general, and Dr Albert G. Hill – MIT research VP, was the head of the board of directors [29].

The U.S. Navy asked the lab to develop a guidance system to use in the Trident I long-range C4 missile, this led to the design of a system with a star-tracker that provided the required accuracy at extended ranges – the missile became operational in 1979. During the 1980s, the lab continued to design guidance systems for missiles, improving the Trident I system with the Mk6 guidance system. For the U.S. Air Force, the labs designed the Missile

Performance Measurement System (MPMS) and the Advanced Inertial Reference System (AIRS) [30]. In 1982 Dr Hill retired and Kenneth McKay succeeded him. The lab started to work with micro-electromechanical systems (MEMS) in 1984, which were very small guidance systems, and in 1987 they worked on the Space Station program. In 1987 Ralph Jacobson, also a retired Air Force General, succeeded Robert Duffy as president and CEO and Joseph Charyk became the chairman of the board. Sadly, Charles Draper passed away that same year and the Charles Stark Draper Prize was created in his honour [31].

90s and Present

In 1989 the Cold War had ended, and the laboratory was forced to make half of its employees redundant due to cutbacks in defence funding and changes to government contracting rules. The lab started to find ways to use its technology in civilian applications which led to them designing robots that could manufacture clothing. This was done to compete with the low-cost of Asian labour [32]. In 1993 low-costing MEMS devices entered the market with plans to use the inertial sensors in products such as camcorders. The lab continued working with NASA helping to configure the Space Shuttle for missions. In 1997 Vincent Vitto succeeded Ralph Jacobson as CEO, he was a physicist with 32 years of experience at MIT's Lincoln Laboratory. That same year the lab created a fly-by-wire system for submarines and demonstrated the first autopilot for submarines. They continued to use MEMS technology for military and civilian products such as gun-launched, guided munitions as well as 2mm-wide microphones. The MEMS technology was also used for medical applications (2000s), the devices could be used to track surgical instruments inside the body. They also researched implanting inertial sensing devices into the ear to improve balance [33].

Today they employ over 1000 scientists and engineers – experts in fields "ranging from GN&C to microfabrication" [34]. They continue to accept government and commercial contracts and advance their work in the medical field.

Chapter 5

Apollo Guidance Computer Design & Specifications

5.1 Design

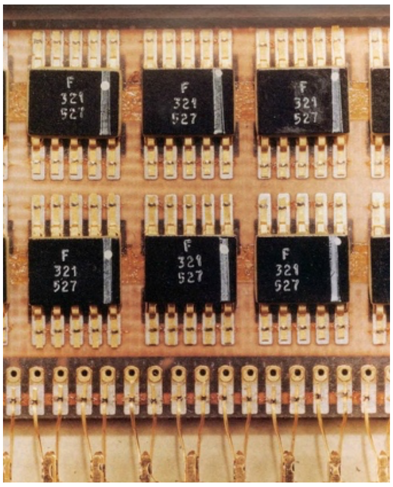

Figure 7: Flatpack silicon ICs in AGC

As previously discussed, the AGC was designed at the MIT Instrumentation Laboratory under Charles Stark Draper. Eldon C. Hall led the hardware design team. The early architectural work came from J.H. Laning Jr, Albert Hopkins, Richard Battlin, Ramon Alonso and Hugh Blair Smith [35]. The hardware for the flight had been developed by Raytheon.

J. Halcombe Laning

J.H. Laning Jr was born on the 14th of February 1920 in Kansas City, Missouri. In 1940 he received an undergraduate degree in Chemical Engineering from MIT where he also completed his PHD. He was an MIT computer pioneer and in 1952 he created an algebraic compiler called George (Laning and Zierler system) that ran on the MIT Whirlwind – the first real time computer [36]. He was the deputy associate director of the MIT Instrumentation Laboratory from 1955 to 1980. While there he helped develop a scheme for doing onboard navigation on the Apollo program's guidance system. He designed the Executive and Waitlist operating system for the Lunar Module Guidance Computer and made it up from cloth. His design saved the Apollo 11 mission when the team started experiencing the 1201 and 1202 errors (this will be discussed in greater detail in a following chapter). Unfortunately, he died on the 29th of May 2012.

Albert L. Hopkins

Hopkins was a computer designer who worked at the MIT instrumentation Laboratory during the development of the Apollo Guidance Computer. He received a PHD from Harvard then went on to be the Assistant Director at the laboratory. He was part of the group who designed the Apollo Guidance Computer [37]. After retiring from the MIT lab, he opened a pottery and antiques shop with his wife in South Danbury, New Hampshire. He died on the 17th of May 2016.

Richard Battlin

Richard "Dick" Horace Battlin was born on the 3rd of March 1925 in Atlantic City, New Jersey. He was an American engineer and mathematician who helped lead the design of the Apollo Guidance Computer. He started working at the MIT Instrumentation Laboratory in 1951 as an assistant director. In 1956 he left to work for Arthur Little Inc but soon returned to the lab in 1958. He became the technical director of the Apollo Mission Development program. His team created the analytic and software design for the Apollo Guidance Computer. In 1973 when the lab became the Charles Stark Draper Laboratory he served as the associate head of the NASA Program Department. Following his retirement from the lab he continued to teach aeronautics and astronautics at MIT until 2010. He died on the 8th of February 2014 [38].

Raytheon

Raytheon is an American multinational aerospace and defence conglomerate headquartered in Waltham, Massachusetts. It is known as one of the "largest aerospace, intelligence services providers, and defence manufacturers in the world by revenue and market capitalisation" [39]. It was founded in 1922 and focussed on new refrigeration technology but soon moved onto electronics. During World War II they manufactured magnetron tubes that were used in radar systems. After the war they developed guidance systems and guided missiles. They developed flight hardware for the Apollo Program. Today they continue to research and develop products in the aerospace and defence industry such as aircraft engines, missiles and drones.

Design Continued

The Apollo Guidance Computer was the first computer to use silicon IC chips after Eldon Hall advised using them. The first version of the computer used 4,100 ICs – with each containing a single three-input NOR gate. The integrated circuits were from Fairchild Semiconductor, an American semiconductor company based in San Jose, California. They were implemented using resistor transistor logic in a flat-pack – which can be seen in figure 7 above. The circuits were connected using wire wrap and the wiring was embedded in cast epoxy plastic. The Apollo Guidance Computer had 2048 words of erasable magnetic-core memory – RAM, which was used to store temporary results. Each word contained 16 bits: 15 bits of data and one odd-parity bit. This means that the AGC had 32,768 bits of RAM. The computer had 72KB of ROM – 589,824 bits, this memory is programmed and cannot be changed once finished. Both memories had cycle times of 11.72 microseconds [40].

5.2 Timing

The computers timing reference came from a 2.048 MHz crystal clock. The clock was halved to produce a four-phase 1.024 MHz clock which was used to perform internal operations. They also divided the 1.024 clock to produce a 512 kHz signal called the master frequency – this was used to synchronise external Apollo systems. The master frequency was further divided using a scaler, this was done to increment the AGCs real-time clock.

5.3 Registers

Central Registers

The AGC had four 16-bit central registers which are listed below:

A: Accumulator – arithmetic and logic results are stored
Z: Program counter – address of the next instruction to be executed
Q: Remained of instruction
LP: Lower product after instructions

Registers

The computer had 12 other registers used in operation:

S: 12-bit memory address register
Bank: 4-bit ROM bank register
Ebank: 3-bit RAM bank register
Sbank: 1-bit extension to bank register
SQ: 4-bit sequence register
G: 16-bit memory buffer register
X: adder input (adder performs 1 arithmetic
Y: second adder input
U: Output of adder
B: Buffer register
IN: four 16-bit input registers
OUT: five 16-bit output registers
[41]

5.4 Instructions

The first version of the AGC (Block I) had 11 instructions. The first 8 were called the basic instructions and the last 3 were extra instructions that could be accessed with a special transfer control instruction.

TC Transfer Control:

This is an unconditional branch to the address specified by the instruction. The return address is automatically stored in the Q register so that the TC instruction could be used for subroutine calls.

CCS Count, Compare and Skip:

This instruction combines many of the requirement for controlling program loops into a single instruction. Using the CCS instruction starts with assigning and initialising an integer counter to some value. Next, the code in the body follows and may or may not use the counter when it executes. The body of the loop ends with the CCS instruction. CCS loads the counter from RAM into the accumulator and takes its absolute value to ensure a positive value and decrements the accumulator. Next, the value in the accumulator is tested against four cases and control is passed to one of four storage locations. Depending on the value of the counter in storage, a different number of words are "skipped" after the CCS instruction [42].

Index:

This instruction is used to add the data received at the address specified by the instruction to the next instruction. It can also be used to add or minus an index value to the base address specified by the operand of the instruction that follows INDEX [43].

Resume:

This instruction is used to return from interrupts, it causes an execution to resume at the interrupted location.

XCH (exchange):

This instruction is used to exchange the contents of the memory with contents of the A register.

CS (Clear and Subtract):

This instruction loads register A with the one's complement of the data referenced by the specified memory address.

TS (Transfer to Storage):

This instruction stores register A at the specified memory address. It is also used to detect and correct overflows.

AD (Add):

This instruction adds the contents of memory to register A and stores the result in A.

MASK:

This instruction performs a Boolean AND of memory with register A and stores the result in A.

MP (Multiply):

This instruction multiplies with contents of register A by the data at the referenced memory address. The high-order product is stored in A and the low-order product in register LP.

DV (Divide):

This instruction divides the contents of register A by the data at the referenced memory address.

SU (Subtract):

This instruction subtracts the data at the referenced memory address from the contents of register A and the results are stored in A.

Source for instructions [44].

5.5 Memory

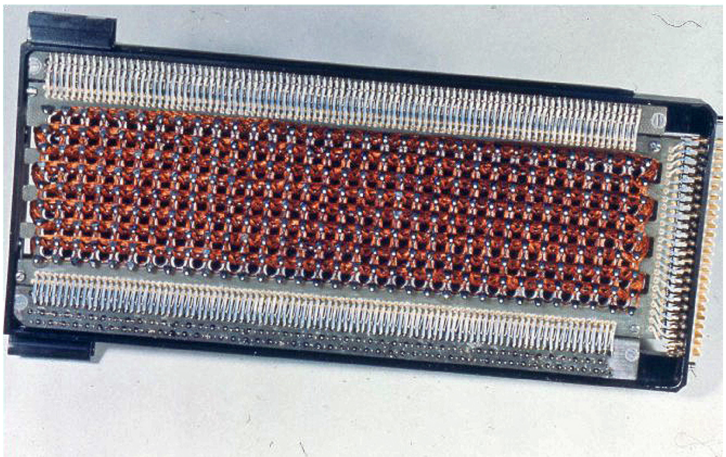

Figure 8: Apollo Guidance Computer Core Rope Memory (ROM)

The original Apollo Guidance Computer's memory was organised into multiple 1 kiloword banks, the lowest bank, bank 0, was the RAM and the banks above 0 were the ROM. The computer originally had 12 kilowords of fixed memory which was later increased to 24 kilowords. Data was transferred to and from memory through the G register – this was called the memory cycle. 15 bits of each memory held the instructions or data and was protected by a 16^{th} odd parity bit. There would be a check during each memory cycle and if the bit did not match the expected value an alarm would light up [45]. To create the core rope memory nickel alloy wire was woven through tiny magnetics "donuts" to create non-erasable memory. If the wire ran through the donut, it was a 1, if it ran around the donut, it was a 0. This process was called the "LOL" method which stood for "little old ladies". This was because woman in the Raytheon factory would weave the software into the core rope memory. Many textile workers were employed to do this. In 1965, a mechanical method was developed but was still extremely slow, one program could take weeks to weave and if there were any errors it would have to be redone. The command module contained 6 sets of core rope and the lunar module had 7. NASA were not happy with this method due to the fact they could not go back and make changes, but the lab informed them this was the way it had to be done as it was how the computer worked.

5.6 Interrupts

Assembled Instruction	Special code	Description
DTCF	DXCH FB and Z	Double Transfer Control Switching the F Bank
NOOP	TCF I+1	No operation by branching to the next instruction in fixed storage
NOOP	CA A	No operation by clearing and reloading the accumulator
OVSK	TS A	Overflow Skip
RETURN	TC Q	Return to Calling Subroutine
SQUARE	MP A	Square the value in accumulator
TCAA	TS Z	Transfer Control to the Address in A
XLQ	TC L	Execute using L and Q registers
XXALQ	TC A	Execute Extracode using A, L and Q registers
ZL	LXCH	Zero the L Register
ZQ	QXCH	Zero the Q Register

APPENDIX B: AGC INTERRUPT VECTORS

Vector Address (octal)	Interrupt Name	Trigger Condition	Description
4000	Startup	AGC power on	Starting address after AGC power up
4004	T6RUPT	TIME6 decremented to 0	Timer for RCS jets, used by the Digital Autopilot
4010	T5RUPT	TIME5 timer overflow	Digital Autopilot timer
4014	T3RUPT	TIME3 timer overflow	WAITLIST task scheduler
4020	T4RUPT	TIME4 timer overflow	DSKY monitoring and updating
4024	KEYRUPT1	Keystroke received from DSKY	Key code from main DSKY is available in channel 15
4030	KEYRUPT2	Keystroke received from secondary DSKY	Key code from Navigation DSKY is available in channel 16 (CSM only)
4034	UPRUPT	Data ready in INLINK register	Used for DSKY uplinks
4040	DOWNRUPT	Downlink registers ready for more data	AGC downlink telemetry
4044	RADARUPT	Data in RNRAD register is ready	Data from rendezvous radar
4050	RUPT10		LM P64 redesignations

Figure 9: List of interrupts for Apollo Guidance Computer [46].

5.7 Standby mode

A power saving mode was created for the AGC controlled by the standby allowed switch. When activated the AGC would power off expect for the clock and scaler. It was used to reduce power during the midcourse of the flight when it was not needed. During the Apollo 11 mission the feature was never used and the AGC was left on during all phases.

5.8 Data Buses

The computer had a 16-bit read bus and a 16-bit write bus. Data from the central registers could be gated onto the read bus. Several registers could be read onto the bus at the same time.

5.9 Block II

Figure 10: Lunar descent and shows Buzz Aldrin receiving communications from NASA headquarters with the block II in the background

The original Apollo Guidance Computer was used for the early Apollo missions such as 1,4 and 6. 1 being the mission where three astronauts tragically died from a cabin fire. In 1966 a second version was created called the Block II – this was the model used for the Apollo 11 moon mission. The Block II version used 2,800 ICs, each with dual three-input NOR gates. The basic architecture of Block I was retained for the new block II model. The upgrades included the ram increasing from 1 to 2 kilowords and the rom increased from 24 to 36 kilowords. This was done so they could expand the instruction set. Even with these upgrades they still struggled with memory problems, so they came up with a few tricks to get around this and squeeze in more instructions. An example of this was to have special memory addresses which when referenced would implement a certain function. For instance, an INDEX to address 25 triggered the RESUME instruction to return from an interrupt. The Block II had the EDRUPT instruction – which was named after Ed Smally, the programmer who requested it. This instruction was used to perform two actions that are common to the interrupt processing.

Chapter 6

Margaret Hamilton

Figure 11: Margaret standing next to software listings she and her team produced for the Apollo project

When you think of the moon landing mission the first name to come to mind is probably Neil Armstrong. However, Margaret Hamilton is an equally important figure if not more important to the success of the mission.

Margaret Hamilton is an American computer scientist; she was born on the 17th of August 1936 in Indiana. Sher family later moved to Michigan where she graduated from Hancock High School in 1954. She first attended the university of Michigan to study Math's but ended up transferring to Earlham College where she achieved her BA in mathematics with a minor in philosophy (1958). Her mother also studied at Earlham College [47]. She was inspired to do philosophy minor by her father who was a philosopher and her grandfather – a headmaster and Quaker minister [48].

She met her first husband, James Cox Hamilton while at Earlham and taught high school mathematics while he completed his undergraduate degree. They then moved to Boston where her husband completed his master's degree in chemistry and had a daughter together. Her husband graduated from Harvard Law School in 1963 but in 1967 they got divorced. In 1967 Margaret married Dan Lickly.

In Boston, Margaret had intended to enroll in graduate study of abstract mathematics however in the summer of 1959, she began working in the meteorology department of MIT where she developed software for predicting the weather [49]. From 1961 to 1963 she worked on the Semi-Automatic Ground Environment (SAGE) Project at the MIT Lincoln

Lab. Here she wrote code for the XD-1 computer that the U.S Air Force used to search for enemy aircrafts [50]. This project was the reason she was a candidate for the lead developer position at NASA. Hamilton went on to join the MIT lab and ended up working on the apollo program. She was initially hired as a programmer but moved into systems design. She was put in charge of the command module software which was the navigation and lunar landing guidance. Her code was responsible for saving the moon mission which will be discussed further in the following software chapter. In 1976, she founded a company called Higher Order Software where they developed ideas for error prevention and fault tolerance. They created a product called USE.IT that was used in multiple government programs. In 1985 she left the company and founded Hamilton Technologies in Cambridge, Massachusetts [51].

She was given credit for coining the term software engineering, during the early apollo mission's software development was not taken as seriously compared to other engineering sectors and was not regarded as a science. She changed this view. In 2016 she received the medal of Freedom from President Barack Obama for her work during the Apollo missions.

Chapter 7

Software

The software for the Apollo Guidance Computer was written in assembly language and stored on rope memory. Rope memory is a form of read-only memory was initially used for NASA mars probes. The majority of the software was on the rope memory which meant it could not be changed during the mission. Some of the key parts of the software were stored in the standard read-write memory in case it needed to be overwritten [55], which the astronauts could do using the DSKY interface. There was a peak workforce of 350 people for software development.

The software needed to meet the Apollo Guidance Computer's requirements did not exist and therefore had to be designed from scratch. A simple real-time operating system was designed by J. Halcombe Laning, a batch job-scheduling using cooperative multi-tasking [56] and an interrupt-driven pre-emptive schedular called the Waitlist – this could schedule multiple timer-driven tasks.

A software interpreter was developed by the MIT Instrumentation Laboratory, it implemented a virtual machine with more complex and capable pseudo-instructions than the actual guidance computer. The instructions were used to simplify the navigational problems. More instructions had been provided by the interpreter which led the AGC's memory being increased. Interrupt-driven user interface routines were created to provide keyboard and display services for the jobs running on the computer, this was called Pinball. A set of user-accessible routines were provided to let the astronaut display the contents of different memory locations, this could be viewed in octal or decimal.

Much of the trajectory and guidance algorithms used were based on the earlier work of Richard Battlin [57]. Alex Kosmala led the development of the first command module flight software, which was called CORONA. The software for the lunar missions consisted of COLOSSUS for the command module, the development for this was led by Frederic Martin. The LUMINARY software on the lunar module was led by George Cherry. The details of these programs were implemented by a team led by Margaret Hamilton [58].

Margaret was very interested in human error which led her to develop countermeasures for this. Her priority display that had a knock-on risk that the astronaut and computer would be out of synch when it mattered most. When alarms would go off and priority displays replaced the original once, the actual switch over would be happening a step slower. To counter this her solution when seeing a priority display was to count to five. Another example was that she wrote the software so that the computer would recognise when it was being asked to perform more tasks than it could. An alarm would sound which would alert the astronauts that it is being overloaded and will continue with the more important tasks. Margaret herself said that without this feature the landing would not have been as successful [59].

The software written for the Apollo Guidance Computer influenced the design process for the Skylab, Space Shuttle and early fly-by-wire systems. The code is available to look at on GitHub after being uploaded by a former NASA intern in 2016.

Chapter 8

DSKY Interface

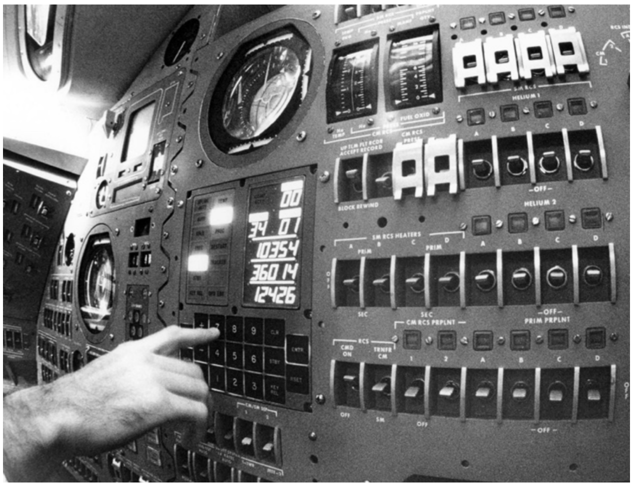

Figure 12: DSKY Interface

8.1 DSKY Interface

A user interface was created for the Apollo Guidance Computer, this was called the DSKY which stood for display and keyboard. The interface had numeric displays, indicator lights and a calculator-style keyboard. To use the device, commands were entered using the keyboard as a two-digit numbers, first being the verb and second the noun. The verb described what type of action would be performed and the noun specified which data would be affected by the action specified from the verb command. The numbers could be displayed on the interface in octal or decimal. The verbs and nouns would be translated into instructions for the spacecraft. The instructions were built into the computer's ROM memory and were compiled using Luminary – the software developed by Margaret Hamilton's team [60].

Each digit was displayed with a green high-voltage electroluminescent seven-segment display – which were driven by relays which limited the update rate. The display was used to display vectors such as the altitude of the craft or a required velocity change.

The command module had two DSKYs connected to its guidance computer. One was located on the main instrument panel. The second was located in the lower equipment bay near a sextant that was used for aligning the inertial guidance platform. The lunar module only had one DSKY for its computer.

Below I have included a link to try simulating the computer for yourself:

https://svtsim.com/moonjs/agc.html

Chapter 9

Timeline

1930-1940s

- Dr Charles Stark Draper created teaching lab for his aeronautics classes at MIT
- Overtime became a full-time laboratory to develop instrumentation for aircraft investigation
- WW2 – the lab expands and moves to an old shoe polish factory
    - Became known as Confidential Instrumentation Development Laboratory
    - Producing early guidance systems and gyroscopic equipment

1950s

- The lab designed and built a small prototype probe that they hoped would fly to Mars
    - Probe was based on inertial systems that had been used for ballistic missiles, submarines and aircrafts that had been built for the military during WW2
- The lab approached the US air force with their probe.
    - US air force were trying to get out of the space business, suggested they talk to newly formed NASA
- Dr Draper held a meeting with NASA leaders to discuss long term plans
    - Discussed how lab's design would fit into a spacecraft piloted by humans
    - Several meetings took place, and it was decided an astronaut should have a role in piloting the spacecraft
    - Led to the concept of having a guidance computer with controls and a display
    - Another reason for this was due to fear the Soviet Union would interfere with the communications between the spacecraft and the ground, endangering lives and the mission

Early 1960s

- April 1961, President John F Kennedy challenges NASA to land on the moon and return safely to Earth – before the end of the decade
- The MIT Instrumentation Laboratory sign the first contract for the Apollo program to build the guidance and navigation system
    - Were unsure of the job at hand but knew they were one of the only ones in the world with a suitable computer
- Lunar orbit concept was picked – this is where the lander would separate from the command module and land on the moon.
    - Led to the question of needing another guidance system for the lunar module but the lab convinced NASA they could use a duplicate AGC in the lunar module
- A big worry was the reliability of the computer. The lab suggested having 2 computers on board – one being a backup. NASA rejected this as they were already having weight issues. The labs fix was to simply make the computer reliable which put a lot of pressure on them

Fall of 1964

- Lab started to design improved version of AGC – took advantage of new technology
- Integrated circuits invented in 1959 – were smaller and more reliant
  - They replaced the core transistor circuits in the earlier design taking 40% less space
- Issue with memory, Mars probe had 4 KB of fixed memory and 256 words of RAM, this was upgraded to 36 KB and 2000 words of RAM
- Was able to upgrade the memory using new core rope memory as discussed earlier
- No last-minute changes were allowed as the memory would have to be re-woven

1965+

- On the 22nd of September 1965 the Block I model of the AGC was installed on a spacecraft.
  - Original software called CORONA was released January 1966
  - First flight took place on the 25th of August 1966
- After less than 2 dozen spacecrafts took flight NASA authorised building 75 computers and 139 DSKYs. 57 of the 102 interfaces were of Block II design [61]
- After rigorous testing took place and successful test flights the AGC was approved for the mission to the moon

Chapter 10

Apollo 11 and the 1201 & 1202 Program Alarms

Figure 13: Apollo 11 launch

Launch and Lunar Orbit

On the 16th of July 1969 the Apollo 11 launch took place. An estimated one million viewers watched from the vicinity of the launch site and many more millions watched from home (25 million American viewers [62]. It was the fifth crew mission of the Apollo program.

On the 19th of July the Apollo 11 passed the moon, and its propulsion engine was fire ready to enter lunar orbit. This is where the computer became most important, helping guide the craft to the moon. On the 20th of July astronauts Buzz Aldrin and Neil Armstrong entered the lunar module and began their lunar descent.

1201 & 1202 Program Alarms

Five minutes into the lunar descent the lunar modules guidance computer began to generate errors. The two errors that appeared were the 1202 alarm which meant “Executive overflow – NO CORE SETS” [63] and then a 1201 alarm which meant “Executive overflow – NO VAC AREAS. What these errors meant in basic terms was that the computer could not complete all its tasks in real-time and some had to be postponed. Back on the ground, computer engineer Jack Garman told Guidance Officer Steve Bales it was safe to descent, so the crew continued with the mission. The response to these errors was to restart the guidance computer. The cause for the errors was determined to be a “rapid steady stream of spurious cycle steals from the rendezvous radar” which had been intentionally left on standby during descent in the case that it was needed for an abort [64]. At this point the processor would normally be nearly 85% loaded but the extra cycle steals added an additional 13% load. Buzz

Aldrin had given the command 1668 which would calculate and display the DELTAH (difference between altitude sensed by the radar and computed altitude), but this added another 10% load which caused the overflow and 1202 alarm. After contacting Houston Aldrin was given the go to re-enter the command, this also resulted in a 1202 alarm. The computer had been coded to deal with problems such as this, the computer used priority scheduling which meant that lower priority tasks were deleted to complete the more important tasks. The computer was able to recover automatically due to the software. Megan Hamilton's priority alarm displays would interrupt the astronauts normal display when there had been errors and would give them a go- or no-go decision on whether to land. Due to Jack Garman recognising the meaning of the errors the crew were given the go to continue with their descent and the mission was successful with the craft landing at 20:17 on the 20th of July 1969.

Hindsight

During the mission the cause was thought to be the rendezvous switch being in the wrong position, but Don Eyles concluded in 2005 that this was not the case. The error that had occurred during the lunar descent was not a pilot or programming error. It was a "peripheral hardware design bug" and had been documented by Apollo 5 engineers [65]. Due to the problem only occurring once during testing it was concluded that it was safer to fly with this hardware then creating a new untested system. Margaret Hamilton had said that it was not the fault of the computer and that the computer had operated as it should have, recognising the errors and following the recovery programs that had been coded into the software to fix the problem.

Chapter 11

What else was it used for?

The Apollo Guidance Computer also played a role in the development of other vehicles which will be discussed below.

Fly-by-wire

Figure 14: Fly-By-Wire system in an F8 crusader

The computer was used as the basis of a fly-by-wire system that was installed into an F-8 Crusader. The computer was used during the first phase of the program but was replaced with a different system during the second phase. The research that was done for this program led to the development of fly-by-wire systems being used for the Space Shuttle [66].

Deep-submergence rescue vehicles

Figure 15: US Navy submergence vehicle

The computer was also used for the basis of the US Navy's deep submergence rescue vehicle [67].

Chapter 12

Navigation before Apollo

Figure 16: 17th Century map of America

Navigation is the process of getting from point A to point B. People make use of vehicles and vessels to make their journey quicker and more efficient. In 3500 B.C boats were used to carry good for trade and this is one of the first records of navigation. Early navigators would stay close to the sore and use sight of landmarks to navigate through territory. Without the sight of land navigators were able to determine their latitude by using the height of the sun during the day and the North Star at night.

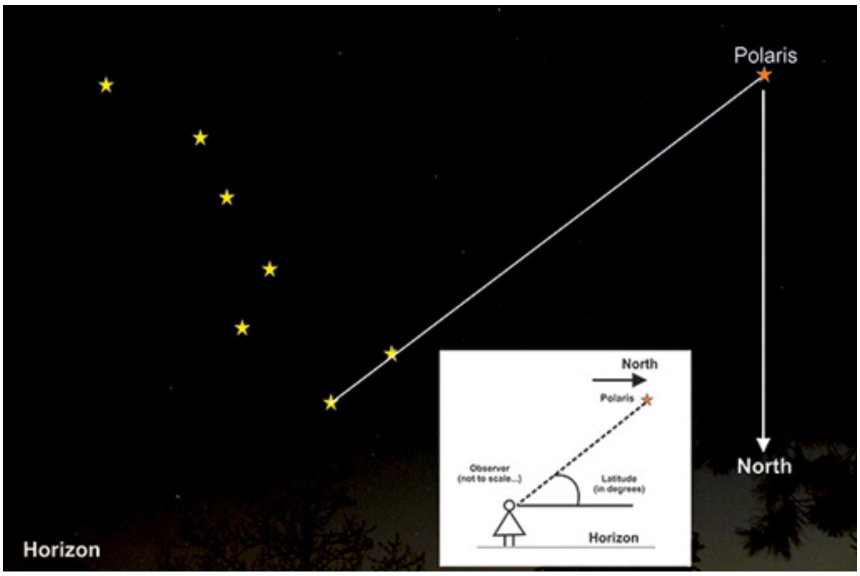

Figure 17: Example of how stars are used to navigate

Phoenicians were the first known western civilisation to use navigation 4000 years ago, they used primitive charts and observations of the sun and stars to determine directions. They would use the North Star (Polaris) and other constellations to figure out their location. Sailors used tools such as a quadrant, they this to find the latitude of their ship from the North Star. Another tool used was an astrolabe, sailors used this with the sun to also figure out their latitude. Finding out the latitude was useful to sailors as they could use this to see how far north or south their ship was. Longitude was also used as early sailors could find out their east and west position. A major advancement was at the end of the 15th century where the Portuguese Bartolomeu Crescêncio invented the chip log. The log would be tossed overboard, and the pilot could count the knots that were let out over a specific period of time. Using this they could determine the ships speed and that is why today we still use knots as a speed measurement. In 1764 John Harrison created a chronometer, this device would allow navigators to find their longitude while at sea.

In 1935 Robert Watson-Watt, a British physicist, produced the first practical radar system. This was used to find objects and could determine the range, position in space, size, shape, velocity and direction of motion. Between 1940 and 1943 the US developed Loran (long range navigation) that pulsed radio transmissions between stations that were received onboard and recorded as waves. The distance between waves corresponded to the difference in time between arrival of the signals from the two stations.

Loran was used by US ships but was very expensive. It was soon phased out by GPS (global positioning system) which was created in 1973. GPS is a space-based radio navigation system that uses 24 satellites to provide accurate positioning, velocity and time worldwide. This worked in a similar was to Loran but used the satellites to receive the signals [68].

This brief insight gives an idea of what navigation was like for early explorers and before we had the advanced technology of today's times.

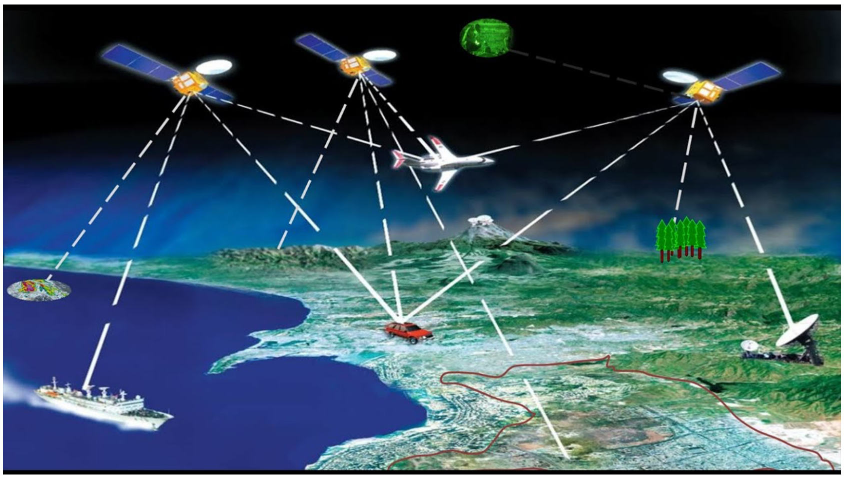

Figure 18: Simple example of how GPS works

Chapter 13

Conclusion

From this paper we have looked at navigation and the purpose of the Apollo Guidance Computer. We have discussed the people behind developing the computer and their history. We have discussed what the purpose of the device was during the Apollo 11 mission. We have an understanding of where the computer was created and how it was developed. Without this piece of technology and the people discussed in the previous chapters this mission would not have been as successful as it was.

This paper has given a deeper understanding of the work that went into this historic computer. Most people overlook or would not know of the people involved such as Margaret Hamilton and Charles Draper and their contribution. By reading this paper we can see how crucial they were and the important roles they played in the success of the Apollo 11 mission.

From this paper we also get an understanding of what navigation is and why it is important – especially in space. I hope that it has been a fascinating read and that you have learnt something that you may have not previously known.

I will leave you with the most famous quote from the mission: “That’s one small step for man, one giant leap for mankind” – Neil Armstrong.

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